

MEMS structures characterization on PMMA layer using KrF excimer laser micromachining

S. SAADON^{a,b*}, Y. WAHAB^{a,b}, A. T. GUANG^{a,b}

^aAdvanced Multi-Disciplinary MEMS-Based Integrated NCER Centre of Excellent (AMBIENCE),

^bSchool of Microelectronic Engineering (SoME), Universiti Malaysia Perlis (UniMAP), Malaysia

This paper presented the study of MEMS structures characterization on PMMA layer by using the 248nm Krypton Fluoride (KrF) excimer laser micromachining. To study surface quality of PMMA, the microdrilling process was carried out to produce the holes. By using the KrF excimer laser, the relationship between the ablation parameter and the size of the holes was investigated. To further confirm the relationship between ablation parameters and the surface quality, several microchannels of the microfluidic structures were fabricated by varying the energy and frequency in order to obtain the optimize parameters. The width of the microchannels increased when the energy increased. After the micromachining process, the microchannels were fabricated again by different beam size. The increment in beam size caused the width of the microchannel to be increased. The physical deformation of the holes and the microchannel were observed by using the High Power Optical Microscope.

(Received August 17, 2015; accepted September 9, 2015)

Keywords: Micromachining, Microdrilling, MEMS Structures, Microchannels

1. Introduction

Micro-Electro-Mechanical System (MEMS) is a small and integrated device which is fabricated through the micromachining technology or micro fabrication technology. MEMS are also known as the micro system technology and are implemented in many fields. Examples of field include medical field, military field and education field. The recent research has showed that the BioMEMS market is expected to be increased from \$1.9B (year 2012) to \$6.6B (year 2018) [2]. This result is written in the BioMEMS 2013 report which mention about the Micro system device market and the application of the MEMS devices in health care [2].



Fig. 1 : MEMS market forecast from year 2012 to year 2018 [3]

The application of the MEMS devices are pressure sensor, accelerometer, flow meter, micro fluidic chips and micro dispensers which is available in the medical field [2]. Market analysis has predicted that the MEMS chips will reach \$22 billion in the year 2018 [3]. Figure 1, indicates the prediction of the MEMS market from year 2012 until year 2018.

From the BioMEMS 2013 report and also the forecast analysis, the micro system technology is penetrated the market for the large variety of the products. There are some list of the MEMS devices and their relative potential market area.

Nimai et al. [5] had conducted the experiment of micromachining on PMMA layer by using the carbon dioxide laser in year 2008. Throughout the experiment, they investigate the effect of the carbon dioxide laser with varies power on the surface of PMMA [5]. The different power of carbon dioxide laser gave impact on the depth and width of the micro channel that produced after micromachining.

In year 2012, another group of researchers did the research about micromachining of MEMS materials by using the krypton fluoride (KrF). The KrF excimer laser was used to do the micromachining process on four different materials those were silicon, soda lime glass, poly-dimethyl siloxane (PDMS) and SU-8 [6].

Table 1. MEMS devices and potentials market areas[1], [4]

MEMS devices	Potential market area
Pressure sensor, Inertial sensor	Automotive, Medical
Accelerometer	Aerospace
Micro Fluidic	Medical, Customer electronic
Micro-optical devices	Measurement, Communication
Flow sensor	Automotive, Medical
RF MEMS	Communication, Aerospace, Defense
Linear actuator	Information technology
IR sensor	Customer electronic, Communication, Aerospace, Defense
Micro-relays and switches	Environment technology
Fluid handling systems	Pharmaceutical industry

During the experiment, the relationship between laser ablation parameter and etch performance were investigated. Examples of the laser ablation parameters included flounce, number of pulses and frequency.

Among all the paper that referred, the two papers that stated above were the favorite papers that help a lot. In this work, the focus would be use KrF laser in the micromachining process on the PMMA layer. The optimized ablation parameters were determined for the PMMA material was the main purpose of this work. The effect of the frequency of the laser toward the uniformity was studied. The effects of the beam size also investigated after obtain the best choice for the better ablation surface quality. To the best of author's knowledge minimal work has been done on this area.

Laser micromachining is a process of ablation which is used to remove the unwanted part of the material that based on the desired design [4], [7]. The ablation process is depending on the materials and the ablation parameters [4]. The laser micromachining does not require the mask to transfer the pattern to wider range of the materials and also provides the high resolution of the images [8], [9], [10].

2. Types of Excimer Laser

There are several types of excimer lasers. Each of the excimer lasers have their own wavelength and are suitable in different application. The common lasers which are used to fabricate the MEMS-related work are the ArF and KrF. Shorter wavelength of the excimer laser results in the better resolution of the pattern or structure that fabricated [4]. The absorption of the laser is related to the wavelength of the laser. This is due to the laser ablation is strongly depended on the absorption of the laser. Thus, among the entire excimer laser, it has to be chosen carefully which lasers can give the maximum absorption. The strong absorption provides slow rate of the material removal.

This allows to control the etch depth by shooting the laser on the material.

Table 2. Types of excimer laser and their relative wavelength [11]

Excimer lasers	Wavelength, λ / nm
Fluorine, F ₂	157
Argon Fluoride, ArF	193
Krypton Fluoride, KrF	248
Xenon Bromide, XeBr	282
Xenon Chloride, XeCl	308
Xenon Fluoride, XeF	351

In the manufacturing field, the excimer laser is used to process the material. In order to process the material or to fabricate the pattern with good resolution, the shorter wavelength of the laser is chosen. Shorter wavelength of the laser makes the beam more focus on the smaller area of the spot [12].

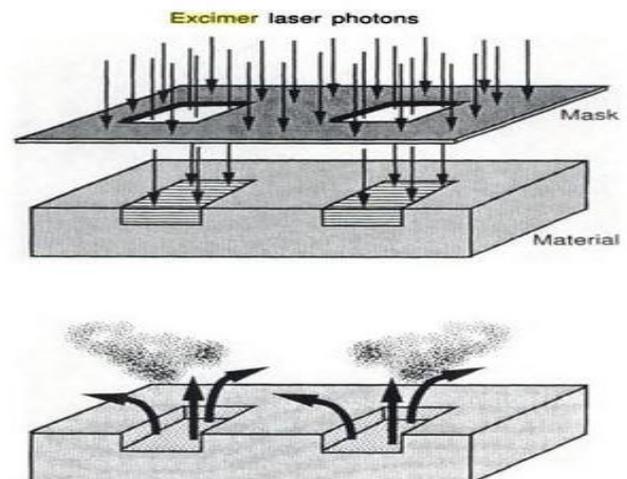


Fig. 2: Excimer laser processing the material [12]

In the fig. 2, the excimer lasers are used to etch the polymer material. When the photon interacts with the polymer, the photon breaks the bonding of the polymer. The excimer lasers are absorbed by the polymer and thus break the weak polymer bonding.

With the application of the laser beam, laser micromachining is used to transfer the pattern design without using the mask. The process step is simple and faster than that that the conventional photolithography. With the correct ablation parameters such as the frequency of the laser, number of pulses and the energy of the laser, the ablation process is started to ablate the silicon substrate.

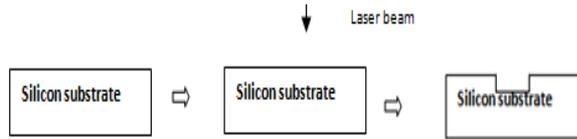


Fig. 3: The Simplified Laser Micromachining

2.1 Ablation on different MEMS materials using Excimer Laser

There are many types of MEMS materials. Different materials have their relatively properties. Thus, when the micromachining process is done on the different materials, the results will be different although the same ablation parameters are used. Four types of materials are chosen as the MEMS materials which are used to investigate the relationship between the ablation parameters and the etch performance by using 248nm of krypton chloride (KrF) excimer laser [6]. The four MEMS materials are silicon, SU-8 photoresist, soda lime glass and PDMS (polydimethylsiloxane). The ablation parameters refer to the number of pulses, fluency and frequency. Throughout these three parameters, the number of pulses and the frequency shows no significant difference in etch rate but the increasing of fluency affect the etch rate to be increased [6].

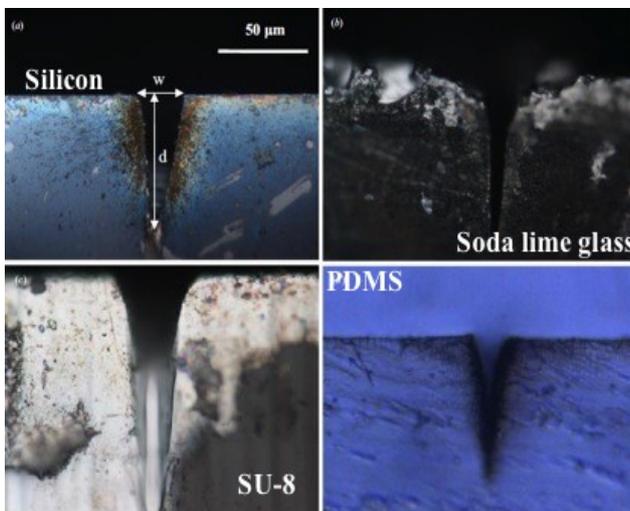


Fig. 4: Images of excimer laser cuts on four materials [6]

Based on the four images in figure 4, the soda lime glass with the damaged which is due to the high repetition of the KrF laser [6]. For silicon and the SU-8 photoresist, the surfaces are dirt free and have soft cut edges [6]. The surface of PDMS is same as the silicon and SU-8 but the only different is that it shows the obvious burnt area.

The chemical name of the PMMA is polymethyl methacrylate, which is a type of polymer. When the methylmethacrylate undergoes the process of free radical polymerization, the PMMA is formed. PMMA is a rapid blazing thermoplastic [5]. If the temperature below the glass transition temperature (T_g), the state is PMMA is glassy [5]. If the temperature is above (T_g), the state of PMMA is rubbery [5]. At the high temperature between 170 degree Celsius and 210 degree Celsius, the deformations of long range of the molecular chains occur [5]. Due to the big zip lengths of the PMMA, approximately 1000 number of monomers per initiation event is produced and the overpoweringly main product of monomer methacrylate is released from the bulk stage [5].

2.2 Application of Excimer Laser Micromachining

KrF laser is used to fabricate ink injection nozzle through the drilling process. In the inkjet printers, it consists of a row of small tapered holes [18]. The purposes of the holes are to squire the ink droplets onto the paper. Better printer quality requires lesser nozzle diameter, smaller whole pitch and broadening the head [18].

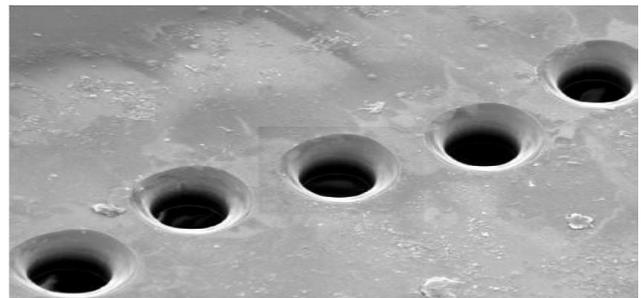


Fig. 5: Nozzles of ink jet printer [18]

The micro applications can be fabricated through the excimer laser micromachining. Generally, the micro structure of the micro applications requires high precision of the patterning. Thus, the integrated circuit with the features below the scale of 500nm is available to fabricate [19].

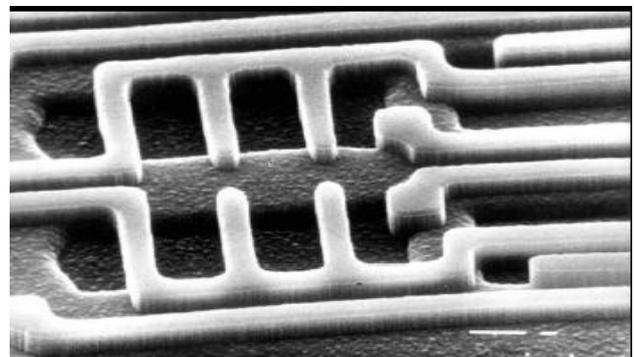


Fig. 6: The microstructure by excimer laser micromachining [19].

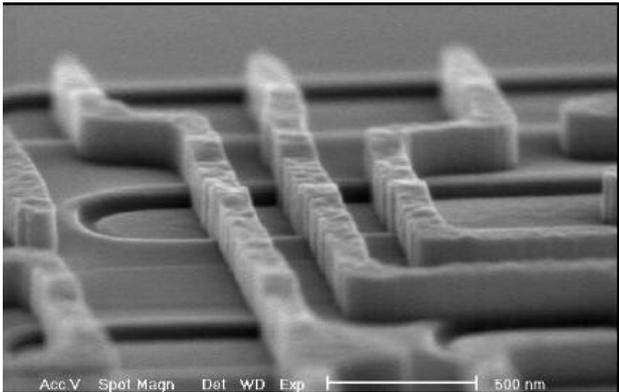


Fig. 7. The sample of integrated circuits with features of below 500nm [19]

3. Experimental Setup

3.1 Sample preparation

Two N-type (100) wafers were prepared. The following step was to cut the wafers into individual die. The Scriber S 2000 (Pioneer Standard (Asia Pacific) Sdn. Bhd) was used to cut the wafers into the size of 2cm x 2cm die. Before the coating process, all die were cleaned by using the BOE solution in order to remove the native oxide and the dirt on the surface of the die. The chemical of 495 PMMA A 2 with 2% in anisole was selected as the photo mask. This 495 PMMA was a positive radiation sensitive resist. When handled this chemical, kept away the chemical from heat, spark and flame as it was flammable. to coat the 495 PMMA on the surface of the die, the equipment used was Spin Process Controller (MIDAS). Several spin speed were chosen to coat the 495 PMMA. The purpose of this process was done was to determine whether the different spin speed would affected the surface smoothness. During the coating process, the spin speed was set as 1000rpm, 1500rpm, 2000rpm, 2500rpm and 3000rpm for duration of 25s. Soft bake process was took place to harden the 495 PMMA layer at 90°C. After the coating process, Atomic Force Microscopy (AFM) for analyzing the surface.

3.2 KrF Excimer Laser microdrilling and micromachining

Microdrilling process was a process to drill a hole. During the process, the pulse number was fixed at the value of 300 and the pulse rate was also fixed at the value of 200. To drill the holes, varies energy of 3mJ, 6mJ, 10mJ, 15mJ and 18mJ were selected and also the frequencies of 10Hz, 50Hz, 100Hz, 200Hz and 400Hz.

At micromachining process, The pattern of the microchannels was designed by using the AutoCAD. The design transferred to the RapidX machine and converted into machine code. The microchannels were fabricated by varying the frequencies, which were 100Hz, 200Hz, 300Hz and 400Hz, and the energies of 3mJ, 8mJ, 15mJ and 18mJ. Again the number of pulses was set to 300 and

the pulses rate was set to 200. After this process, the optimized ablation parameters were determined as shown in Fig 8.

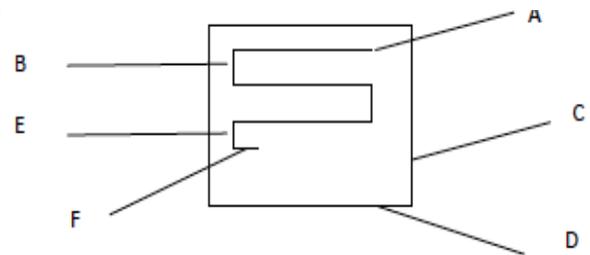


Fig. 8: The design of the microchannel

Table 3: Design specification of the microchannel

Line	Length
A	0.3mm
B	0.1mm
C, D	0.4mm
E	0.05mm
F	0.02mm

In one dice, there was 16 microchannels were fabricated but in different ablation parameters. In this experiment, the optimized ablation parameters were determined. The optimized ablation parameters were used in fabricating the structure of the microchannel. By using the same design as shown in figure 9, six microchannels were fabricated but with the different beam size. The purpose of this experiment was to investigate the relationship between the beam size and the length width of the microchannel. Thus, the sizes of the beam used were 0.1mm, 0.3mm, 0.5mm, 0.8mm, 1.0mm and 5.0mm.

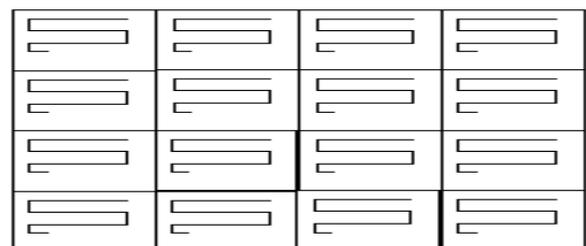


Fig. 9: Design of microchannel in one dice

4. Experimental Results

4.1 Thickness and surface uniformity of PMMA layer

There were several samples undergo the spin coating process with different spin speed setting. According to the datasheet of PMMA, different spin speed setting gave different thickness of the PMMA layer. However, there was no apparatus to exactly measure the thickness of the PMMA. Thus, alternative method was used to

approximate the thickness of the PMMA. The approximated method was to determine the height of the grain size of the PMMA through the Atomic Force Microscopy (AFM). From this method, the approximated thickness of the PMMA layer can be identified. However, the disadvantage of the AFM was the time consumed to measure the sample was long. Therefore, only three samples with different spin speed setting were selected.

The figure 10, figure 11 and figure 12 indicated that the 2D and 3D images under the AFM for three samples. Sample 1 represented the die with the coated PMMA under the spin speed of 1000rpm. The sample 2 was the coated PMMA die with 2500rpm while sample 3 was coated under the speed of 3000rpm.

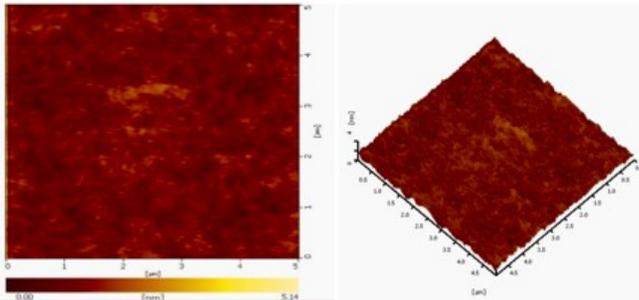


Fig. 10: 2D and 3D images of PMMA coated dice with 1000rpm

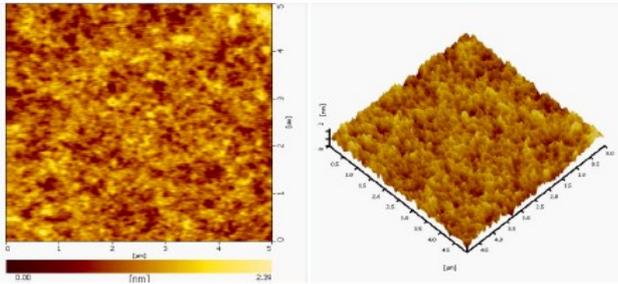


Fig. 11: 2D and 3D images of PMMA coated dice with 2500rpm

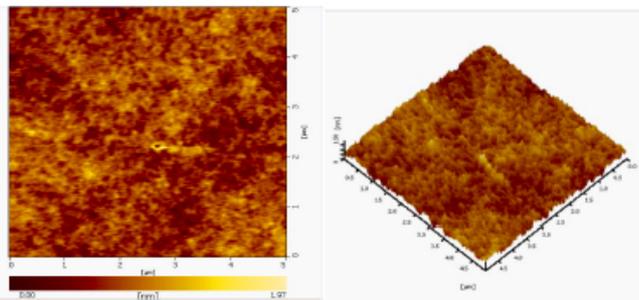


Fig. 12: 2D and 3D images of PMMA coated dice with 3000rpm

Based on the results, the yellow portion represented the highest height of the PMMA while the brown portion represented the lowest height of the PMMA. Different spin speed affected the thickness of the PMMA which coated on the silicon dice. The maximum thickness of the PMMA was the sample 1, which is coated with the speed of 1000rpm, gave the results of 5.14 nm. The sample 2, coated with the speed of 2500rpm, had the maximum thickness of 2.39 nm. The sample 3, coated with the speed

of 3000rpm, had the maximum thickness of 1.97 nm. The spin speed setting was eventually affected the thickness of the PMMA. The lowest spin speed setting had the thickest layer compared to the high spin speed setting. Another extra measurement was carried out using the AFM was the surface analysis. In the surface analysis, the peak and valley regions were investigated. The peak was the highest height of the PMMA while the valley was the lowest height of the PMMA. This data was known as the spacing parameters and this measurement for all the three samples was based on the horizontal features of the PMMA surface. Generally, this was important to optimize the surface quality and to control the void fraction in PMMA materials especially the designer wanted to use the PMMA to design the micro engineering application.

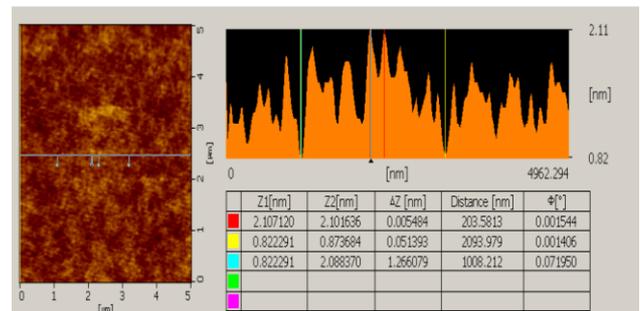


Fig. 13: The surface analysis for sample 1

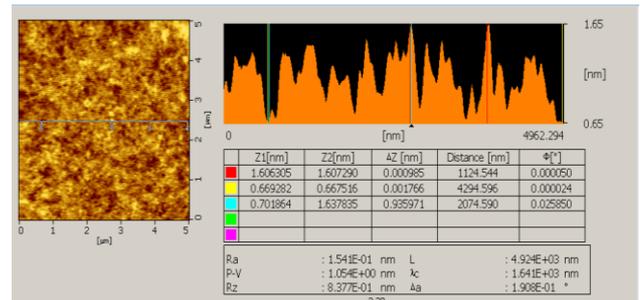


Fig. 14: The surface analysis for sample 2

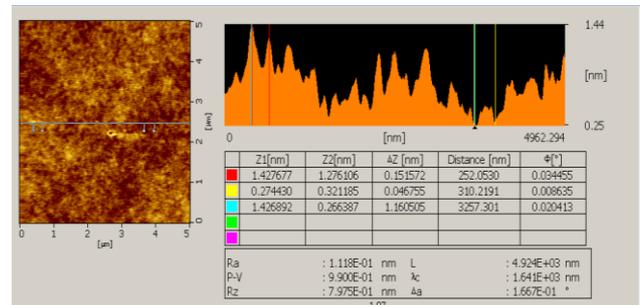


Fig. 15: The surface analysis for sample 3

4.2 Holes surface quality through microdrilling process

The purpose of this step was to investigate the effect of the energy and frequency to the size of the holes and also the determination of the optimized ablation parameters. The Fig. 16 showed the effect of change of the

ablation parameters (energy and frequency) to the surface quality of PMMA.

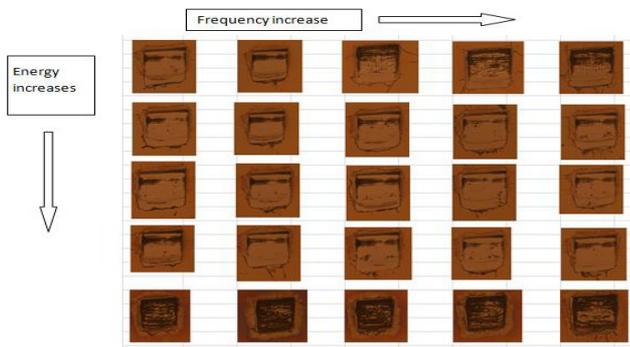


Fig. 16: The images of holes under high power optical microscope

Based on the results that obtained, the effect of the energy of laser showed great impact on the size of the square like pattern compared to the frequency of laser. The low energy of energy provides the small size of the pattern. As the energy of the laser gradually increased, the size of the pattern had clearly shown that the size of the pattern increased. However, when the energy of the laser achieve the maximum energy which was 18mJ (the limitation of the highest energy), the burnt mark area was observed. On the other hand, the frequency did not showed much different on the size of pattern. The frequency cannot show the effect clearly through the microdrilling process. Therefore, the micromachining process was carried out. Actually, from the microdrilling process, the optimized ablation parameters could be obtained. However to further confirm the optimized ablation parameters and also the effect of the frequency on the surface quality, the micromachining process was carried out. Throughout this microdrilling process, the dominant factor to cause the size of the holes to be increased was the energy of the laser compared to the frequency.

5. Conclusion

This paper described the characterization of MEMS structures on PMMA using KrF excimer laser. The focus of the project was to study the surface quality of the structure produced by the KrF excimer laser on PMMA layer. Throughout the project, a simple MEMS structure of the microfluidic structures which was the microchannel was fabricated to determine the optimized ablation parameters. In the sample preparation step, the spin coat technique was used to coat the PMMA with the different spin speed setting. The AFM was used to estimate the thickness of the PMMA as there was no other apparatus to use to measure the actual thickness of the PMMA. The different spin speed setting gave the different thickness of the PMMA. The low spin speed setting (1000rpm) gave the highest height of the grain size which was 5.14nm

whereas the high spin speed setting (3000rpm) had lowest grain size which was 1.97nm.

Acknowledgements

The authors acknowledge University Malaysia Perlis and the Ministry of Higher Education for providing the Exploratory Research Grant Scheme (ERGS)

References

- [1] Henne van Heeren, "MEMS-Recent Developments, Future Direction," Wolfson School of Mechanical and Manufacturing Engineering, Loughborough, 2007. http://www.lboro.ac.uk/microsites/mechan/research/ipm-ktn/pdf/Technology_review/mems-recent-developments-future-directions.pdf
- [2] Laura Wood. (2013, June) BioMEMS 2013 Report: Microsystem Device Market for Healthcare Applications. <http://www.prnewswire.com/news-releases/biomems-2013-report-microsystem-device-market-for-healthcare-applications-211030171.html>
- [3] R. Colin Johnson. (2013, August) MEMS Market to Top \$22 billion by 2018. http://www.eetimes.com/document.asp?doc_id=1320035
- [4] Andrew S. Holmes, "Laser Fabrication and Assembly Processes for MEMS," SPIE Proceedings, vol. 4274, pp. 297-306, 2001.
- [5] Nimai C Nayak, Y C Lam, C Y Yue, Ayan T Sinha, Journal of micromechanics and microengineering, vol. 18, August 2008.
- [6] Kewei Liu, Zhorro NiCkolov, Jonghyun Oh, Hongseok "Moses" Noh, Journal of Micromechanics and Microengineering, vol. 22, December 2011.
- [7] Malcolm C. Gower and Nadeem H. Rizvi, Proc. SPIE 4065, High-Power Laser Ablation III, August 2000.
- [8] Yuhong. Long, Liangcai. Xiong, Tielin. Shi, Zirong. Tang, "Study of Excimer Laser Electrochemical Etching Silicon," Nano/Micro Engineered and Molecular Systems, pp. 16-19, January 2007.
- [9] J.H. Brannon, IEEE Circuits & Devices Magazine, 6(5), 18 (1990).
- [10] L.Q. Li, Y.B. Chen, and X.S. Feng, Chinese optics letters, 1(10), 606 (2003).
- [11] Excimer Lasers. [Online]. http://www.rp-photonics.com/excimer_lasers.html
- [12] R.C.Crater and P.J.Oakley, Laser Processing in Manufacturing, 1st ed. London: Chapman & Hall, 1993.
- [13] Narendra B. Dahotre and Sandip P. Harimkar, "Laser Micromachining," in Laser Fabrication and Machining of Materials. New York, United States of America: Springer Science + Business Media, LLC, 2008, ch. 7, pp. 247-268.

-
- [14] Nadeem Rizvi, David Milne, Phil Rumsby, and Malcolm Gower, Laser Applications in Microelectronic and Optoelectronic Manufacturing V, January 2000.
- [15] Nadeem H Rizvi and Paul Apte, Journal of Materials Processing Technology, **127**(2), 206 (2002).
- [16] Choo Kok Leong. (1999) Micromachining using an excimer (248 nm) laser. [Online]. <http://digital.library.okstate.edu/etd/umi-okstate-1010.pdf>
- [17] Milena Koleva. Poly(methyl methacrylate) (PMMA). [Online]. http://webhotel2.tut.fi/projects/caeds/tekstit/plastics/plastics_PMMA.pdf
- [18] Malcolm C. Gower, "Excimer laser micromachining: a 15-year perspective," Laser Applications in Microelectronic and Optoelectronic Manufacturing, vol. IV, July 1999.
- [19] Ludolf Herbst, Thomas Wenzel Ingo Klafit, and Ulrich Rebhan, "High repetition rate excimer laser for micromachining," SPIE USE V, December 2002.

*Corresponding author: saadonsalem@yahoo.com